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Design and Manufacturing of a Research Magnetic Torquer Rod

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Abstract

Microsatellites are the lowest price spacecrafts for lunch to their orbit and recently they extensively employ in space missions. In this type of satellites it has been tried to use less heavy and simple hardware with higher reliability and energy efficiency. Magnetic torquers are mainly used in Satellite Attitude Control Systems (ASC) as a control actuator. These actuators generate desired controllable torques. The Magnetic torquers have the characteristics of a relatively lightweight and they require no moving parts, expendables, and complex hardware too. These minimum requirements have motivated scientific community to employ actuators in spacecrafts extensively. The present paper dealt with the critical subject of design and manufacturing of these actuators. Accordingly this paper presents design procedures and manufacturing of a research magnetic torquer in Aerospace Research Laboratory of K.N.Toosi University of Technology, Iran. Firstly, a mathematical model for design of a magnetic torquer is explained, and the significant parameters for manufacturing of an efficient actuator are extended. Then design strategic of a magnetic torquer is expanded as a helpful algorithm. After that a sample magnetic torquer is designed and manufactured respectively that the CK30 alloy is employed for its core. CK30 alloy that is used is a different soft magnetic core. At the end, driver and demagnetization circuits are presented and the research magnetic torquer with its participant circuits is discussed.

Keywords: Magnetic Torquer, CK30 Magnetic Core, Driver Circuit, Demagnetization Circuit

Nomenclature

B	: magnetic flux density (Tesla in SI)
H_{Air}	: Solenoid magnetic intensity field
H_{Core}	: Core magnetic intensity field
i	: current
l	: length of the torque rod
L	: inductance
$m_{\max}$	: mass
M	: core magnetization (A/m in SI)
M_{Total}	: magnetic dipole moment (Am2 in SI)
N	: number of turns
N_d	: the demagnetizing factor
P_{Max}	: Maximums power loss
$R_{\min}$	: resistance
r	: core radius
V_{bus}	: voltage
W_{res}	: wire resistivity
μ_0	: permeability of free space
μ_r	: relative permeability of the core material
Φ_B	: magnetic flux
τ	: LR time constant

1 Introduction

Magnetic torquers are one of the most important attitude control subsystem actuators, which have been frequently applied to low Earth orbit spacecrafts. These actuators use usually for despinning or unloading unwanted spacecraft angular momentum [1]. The magnetic torquers used in attitude control subsystem are classified in "free air torquer coils" and "magnetic torquers". Both types of actuators produce magnetic dipole moments, which interact with the Earth's magnetic field to generate external torques on the spacecrafts. This effect is calculated by the expression, $\vec{T} = \vec{M} \times \vec{B}$. In SI units, the torque, $\vec{T}$, in $N-m$ equals the cross product of the magnetic dipole moment, $\vec{M}$, in $Amp-m^2$ with the magnetic field, $\vec{B}$, in Tesla [2],[3]. The soft magnetic core of the magnetic torquers dramatically amplifies the magnetic dipole moment produced by the current loops at the expense of additional weight as compared with free air torquer coils. To damp angular oscillations and to remove spin rates, permeable cores are used which undergo magnetization changes in the geomagnetic field, thus transforming the kinetic energy of the satellite into hysteresis and eddy-current losses [14] and, hence, the choice of the core material is the most important design

parameter. In general, in compare with another satellite control actuators, magnetic torquers are useful because they are substitutes for consumable (such as fuel for thrusters), thus reducing weight [2], [4].
The dependence of magnetic torquer with Earth magnetic field is the most significant attention in design of magnetic torquers. Earth magnetic field respects inverse with cube of altitude from Earth center, so in higher altitude for a same torque, stronger magnetic dipole moment is needed that it causes increasing mass and expenditure power in spacecrafts. For example, in an orbit with $400\,\text{km}$ altitude and a magnetic torquer with $100\,Am^2$ the magnetic torque $1.28\times10^{-3}\,Nm$ is generated, but this actuator in geostationary orbit will generate $5.23\times10^{-4}\,Nm$ magnetic torquer. Thus, Magnetic torquers are widely used in low Earth orbit spacecrafts [8], [9]. Figure 1 shoes separate elements of a magnetic torquer. This paper presents the sequence of design and manufacturing procedures of a magnetic torquer and discusses the results of manufactured sample research magnetic torquer.

Figure 1: a separate magnetic torquer

2 Magnetic torquers Design

First of all, the restricting parameters in the design such as magnetic dipole moment, power loss due to coil resistance, voltage, mass, and also dimension parameters have to be determined. To be able to control the angular momentum of the satellite, the actuator must have enough control authority to overcome on-orbit disturbances such as external torque due to aerodynamic drag, solar radiation pressure and earth's magnetic field as well [3], [10], [11]. Choosing material of magnetic cores has the key role in design of these actuators. In general, magnetic materials can be classified as magnetically soft and hard materials. Soft materials are normally used as the magnetic core materials for inductors, transformers, magnetic torque actuators, in which the magnetic fields vary frequently, whereas hard materials, or permanent magnets, are used to replace magnetization coils for generating static magnetic fields in devices such as electric motors [15].

Current magnetic torquers produced from ferromagnetic alloys such as iron-cobalt or nickel-iron that have a linear relationship between input current and magnetic dipole moment for the majority of their operating range. Ferromagnetic materials, such as Permalloy (78% nickel, 22% iron), and Permendur (50% cobalt, 50% iron) have very high permeabilities and, when used as core materials, lead to a substantial reduction in power consumption as well as bulk. However, ferromagnetic materials have magnetization curves which saturate at relatively low values of applied magnetic field intensity and exhibit both nonlinearity and hysteresis [3], [12]. This is an essential requirement quality in order to provide a simple workable control algorithm for instances in which the direction of the net moment contribution of all torquers must be changed quickly [13]. The relative permeability of the core material is important parameter too. Core with high relative permeability causes a decrease in required power of actuator and reduces its mass. It will exhibit the relationship between magnetic dipole moment and other parameters. In this paper the CK30 alloy is employed as soft magnetic core. The magnetic field intensity, H, within the core comes from two separate sources, the solenoid and the magnetization of the core. It is assumed that the magnetic intensity field is parallel to the long axis of the rod. If the solenoid is very thin ($\frac{l}{r}$ is large), then the magnetic intensity field contribution of solenoid is given by the following equation.

$$H_{Air} = \frac{Ni}{l} \tag{1}$$

Ferromagnetic core in magnetic torquers decreases the magnetic field intensity.

$$H_{Core} = \frac{Ni}{l} - N_d M \tag{2}$$

In which M is core magnetization and the quantity of demagnetizing factor, N_d, is related to the length of the magnetic torquer, l, and core radius, r, [5].

$$N_d = \frac{4[\ln(l/r) - 1]}{(l/r)^2 - 4\ln(l/r)} \tag{3}$$

This is the fundamental equation relating the magnetic flux density to the magnetization. With adding ferromagnetic core, the magnetic flux density will increase.

$$B = \mu_0 (H_{Core} + M) \tag{4}$$

This enables us to eliminate core magnetization, M, as a variable from the previous equation for magnetic flux density, B. This reduces to the following.

$$\frac{Ni}{l} = (1 - N_d) H_{Core} + \frac{N_d B}{\mu_0} \tag{5}$$

The core material that is required needs to have two unique properties: a low enough value for the coercive force that can be considered negligible, and a large region of its hysteresis curve that can be approximated by a linear function [7]. These provisions are necessary in order to both ensure a linear relation between current and dipole moment and ensure that there is little remaining dipole moment produced by the magnetic torquers after they are turned off. With these idealizations, the hysteresis curve can be replaced by the simple relation below [4].

$$H_{Core} = \frac{B}{\mu_0 \mu_r} \quad (6)$$

That μ_r is relative permeability of the core material. Combining this with the expressions from (5) provides a relation between the magnetic flux density, B, and current that is clearly linear.

$$B = \frac{\mu_0 Ni}{l(\frac{l - N_d}{\mu_r} + N_d)} \quad (7)$$

After that, magnetic dipole moment equation is manifestly extracted. The magnetic dipole moment of the magnetic torquer is simply the sum of the dipole moments produced by the windings and by the ferromagnetic core [5].

The windings can be idealized as N separate current loops while the total moment from the magnetization is simply the average magnetization times the rod volume.

$$M_{Total} = \pi r^2 (Ni + lM) \quad (8)$$

Combining this equation with expressions from (6) and (7) yields expressions for the moment as both a function of the magnetic flux density, B , and as a function of current, i .

$$M_{Total} = \pi r^2 Ni \times (1 + \frac{\mu_r - 1}{1 + (\mu_r - 1)N_d}) \quad (9)$$

When power loss, P_{Max} , and voltage, V_{bus} , parameters are determined solenoid resistance drives as expression(10).

$$R_{\min} = V_{bus}^2 / P_{\max} \quad (10)$$

The total length of wire is found with respect of wire resistivity, W_{res}.

$$l_{Wire} = R_{\min} / W_{res} \quad (11)$$

The number of turns can defined in terms of l_{Wire} only.

$$N = \frac{l_{Wire}}{2\pi r} = \frac{R_{\min}}{2\pi r W_{res}} \quad (12)$$

Replacing the current, i , with expression $V_{bus} / R_{\min}$ and Combining it with equation (9) yields expressions for the magnetic dipole moment as function of core radius, r .

$$M_{Total} = \frac{rV_{bus}}{2W_{res}} \times (1 + \frac{\mu_r - 1}{1 + (\mu_r - 1)N_d}) \quad (13)$$

The dependence of magnetic dipole moment with voltage, $18\ volt$, relative permeability of the core material 2000 ,and resistivity of the wire $0.538\ \Omega / m$ is graphically illustrated in Figure 2. Therefore, with respect to Figure 2 specified that decreasing of core radius and increasing the length of the magnetic torquer causes increase magnetic dipole moment parameter.

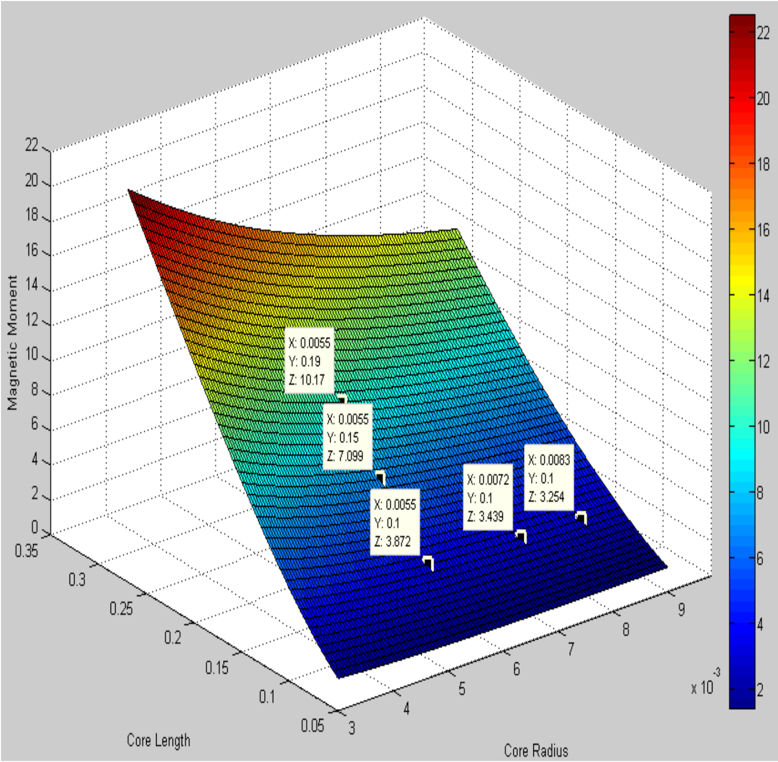

Figure 2: dependence of magnetic dipole moment whit length and radius of core

Next important step in design of magnetic torquers is computation of inductance. The inductance is calculated as the change in magnetic flux divided by the change in current

$$L = \frac{\Delta\Phi_B}{\Delta i} = \frac{\mu_0 \pi r^2 N^2}{l(\frac{1}{\mu_r} + N_d)} \tag{14}$$

When control signal is performed in actuator, the rate of its response given with time constant, τ .

$$\tau = \frac{L}{R} \tag{15}$$

In which R represents actuator resistance in this expression. After the magnetic torquer shuts off, the current will experience natural decay like any simple LR circuit, so time constant is a significant parameter in control algorithm. Favorite desire in actuator design is decreasing the time constant thereupon the rate of response of control algorithm will increase [6].

3 Design Strategies

After explaining magnetic torquer principles, design strategy is the next needed step for manufacturing of magnetic torquers. Design strategy delineates first required parameters for design and shows steps of design regularly. In the rest of this section, magnetic torquer design algorithm is remarked.

To estimate primary design parameters, V_{bus}, P_{MAX}, $m_{\max}$, M_d, and limitation of actuator dimensions are needed for starting the design algorithm. Figure 3 shows design algorithm of a magnetic torquer.

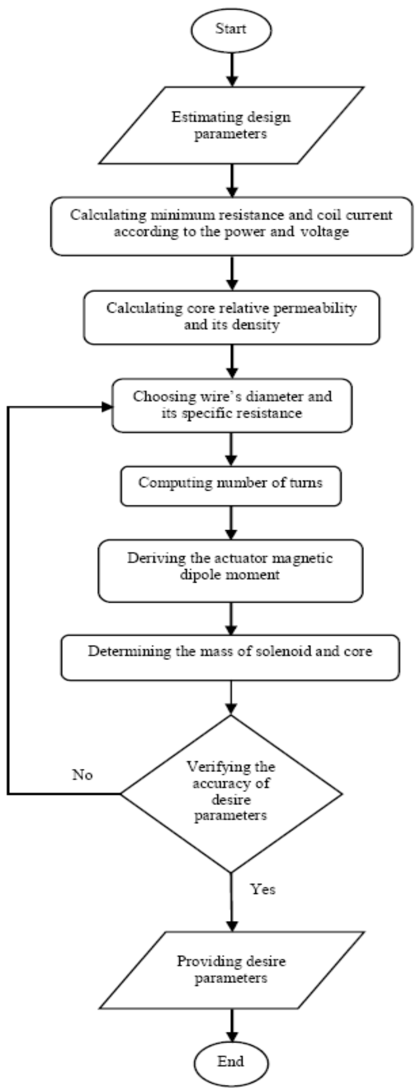

Figure 3: Magnetic Torquer Design Algorithm

4 Manufacturing a Research Magnetic torquer and Its Experimental Creating Setup

The experimental design setup of magnetic torquer is with the respect of Figure 3. Accordingly the sample research magnetic torquer rod is designed and manufactured.
The sample research magnetic torquer parameters are demonstrated in table 1.

Table 1
Magnetic Torquer Specifications

Initial Parameters

Voltage (v)	24
Power (Watt)	1.6
Dipole Moment (Am2)	22.6
Length (cm)	29
Radius (cm)	1.5
Mass (gram)	650

Designed Parameters

Resistance (Ω)	6.5
Wire's Diameter (m)	2090
Wire Cross Sectional Area(m2)	2.827×10^{-7}
Current (A)	0.5
Inductance (Henry)	0.409
Time Constant (s)	0.063

The driver circuit is necessary to turn on magnetic torquers. Electrically, a magnetic torquer represents a load of sizable inductance similar to a DC motor. Driver circuit can be switched on and off and changed direction of the current flow as well. H-Bridge circuit is the most applicable as torque coil driver. H-Bridge circuit for this sample actuator shows in figure 3.

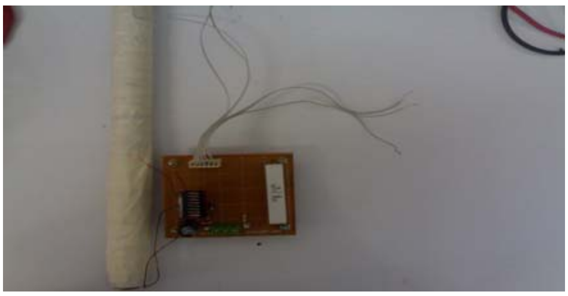

Figure 3: Driver Circuit

This H-Bridge circuit needs protective diodes. While the shutting off the magnetic torquer, the inverse voltages impact the circuit, so protecting diodes are necessary for driver. In core magnetic materials there is a nearly linear behavior of B-H on the demagnetization curve. Core magnetic residual, after shutting off the actuator, is unfavorable deal. In magnetic materials the second quadrant of hysteresis curve is most important and is called demagnetization curve. Reduction of induction to $B=0$ in core is desired. This is obtained practically by the application of an alternating field of decreasing amplitude. The major problem yet to be solved in the design of the magnetic torquers is to find a core magnetic material with the necessary linear hysteresis curve behavior. Demagnetization circuits are other ways to eliminate core magnetic residual. This circuit is shown in figure 4.

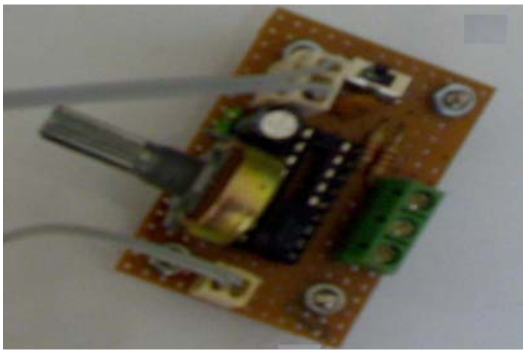

Figure 4: Demagnetization Circuit

5 Conclusions

Magnetic Torquers are frequently used as attitude control system actuators for spacecraft in LEO orbits. This paper presented mathematical principles and design strategy for magnetic torquers. Accordingly a sample magnetic torquer is designed and manufactured with $22.6Am^2$ magnetic dipole moment that its parameters showed in table 1. For manufacturing this actuator $CK30$ alloy used that this is a different soft magnetic core. After manufacturing actuator, it was needed driver circuit for turn on and control circuit flow direction. This paper discussed core residual and its importance for control law too. Therefore demagnetization circuit applied to produce an alternating field of decreasing amplitude after shut off the actuator for removing the core magnetic residual. Demagnetization circuit is an accurate applicable way to eliminate core residual. A new method introduced to remove the core magnetic residual.

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